

THE EXTRAGALACTIC INFRARED BACKGROUND

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Abstract

Current limits on the intensity of the extragalactic infrared background are consistent with the expected contribution from evolving galaxies. Depending on the behaviour of the star formation rate and of the initial mass function, we can expect that dust extinction during early evolutionary phases ranges from moderate to strong. An example of the latter case may be the ultraluminous galaxy IRAS F10214 + 4724. The remarkable lack of high redshift galaxies in faint optically selected samples may be indirect evidence that strong extinction is common during early phases. Testable implications of different scenarios are discussed; ISO can play a key role in this context. Estimates of possible contributions of galaxies to the background under different assumptions are presented. The COBE/FIRAS limits on deviations from a blackbody spectrum at sub-mm wavelengths already set important constraints on the evolution of the far-IR emission of galaxies and on the density of obscured (“Type 2”) AGNs. A major progress in the field is expected at the completion of the analysis of COBE/DIRBE data.

Observational constraints

Observations of the extragalactic IR background are severely hampered by the presence of bright foregrounds. Even when measurements are made from space with cryogenically cooled instruments, and in favourable directions (far from the galactic plane and from the ecliptic plane) the extragalactic flux is overwhelmed by zodiacal light and starlight at near-IR wavelengths, by interplanetary dust emission in the mid-IR, and by interstellar dust emission in the far-IR/sub-mm.

The available observational information on extragalactic background radiations over the full range from radio to γ -rays is summarized in Fig. 1. At sub-mm wavelengths, tight upper limits come from the absence of detectable deviations from a blackbody spectrum in the COBE/FIRAS measurements (Mather *et al.* 1994). The derivation of accurate limits to the extragalactic background is complicated by the fact that its spectrum in this region is similar to that of the emission from our own Galaxy, so that there is some ambiguity in the subtraction of the latter. The dot-dashed line shows the estimate of Wright *et al.* (1994), derived assuming that the Galactic emission obeys a simple cosecant law.

At higher frequencies, we have plotted as upper limits the total observed sky brightnesses at different frequencies measured by COBE/DIRBE in a dark direction (Hauser *et al.* 1991), since it is well known that most of the observed flux is due to foreground emission. These limits will obviously become much tighter when the analysis of these data and the subtraction of foregrounds will be completed.

Also shown are the results of the rocket experiment by Lange *et al.* (1990) at 100, 135 and $275\mu\text{m}$, for which a subtraction of the foreground emission has been carried out and an indication of a truly extragalactic signal at the intermediate wavelength has been reported.

The estimated contributions of zodiacal light, interplanetary dust emission and light from unresolved Galactic stars have also been subtracted from the total near-IR sky brightness observed with the rocket-borne experiments of Matsumoto *et al.* (1988) and Noda *et al.* (1992). Using an improved model of the Galaxy, Franceschini *et al.* (1991a) concluded that the starlight contribution might have been underestimated by Noda *et al.* (1992) and that only upper limits could be set on any residual, possibly extragalactic, component; the derived limits are plotted in Fig. 1. Matsumoto *et al.* (1988) reported a possible measurement of the extragalactic component at $2.28\mu\text{m}$ [not confirmed by Noda *et al.* (1992)] and at $3.8\mu\text{m}$ (plotted in Fig. 1).

As pointed out by Stecker *et al.* (1992), observations of very high-energy (TeV) γ -rays in the spectra of blazars provide interesting constraints on the intensity of the extragalactic IR background. The point is that a flux of extragalactic γ -rays is attenuated by interactions with ambient photons leading to the production of an electron-positron pair, occurring primarily

when the product of the two photon energies is $\approx 0.5 \text{ MeV}^2$; for TeV photons, the attenuation is thus primarily due to IR photons. The method has been applied by Stecker & de Jager (1993), de Jager *et al.* (1994) and Dwek & Slavin (1994) by exploiting the detection of the BL Lac object Mrk 421 at TeV energies using ground based Cherenkov detectors. These data show some evidence of a spectral cutoff at a few TeV; the corresponding value of the optical depth to pair production may comprise contributions intrinsic to the source and therefore translates in an upper limit on the energy density of the IR background. Shown in Fig. 1 (short-dashed curve) are limits derived by Dwek & Slavin (1994).

A lower limit to the background flux at $2.2 \mu\text{m}$ (also shown in Fig. 1) comes from an integration of the deep K-band counts of galaxies (Gardner *et al.* 1994). Since these counts are already relatively flat at the faintest magnitudes, the additional contribution from galaxies below the detection limit is probably not very large.

Altogether, simple estimates consistent with these limits (dashed curve in Fig. 1, with the peak at $\sim 100 \mu\text{m}$ due to dust emission and the peak at $\sim 1 \mu\text{m}$ due to starlight) suggest a global contribution of galaxies to the extragalactic energy density in the range $1 \text{ mm}^{-1} \mu\text{m}$ of

$$\epsilon_{\text{IR}}(z=0) \approx 1.2 \times 10^{-14} \text{ erg cm}^{-3},$$

within a factor of a few. This is much higher than the energy density of the “astrophysical” background (as opposed to the “cosmological” microwave background which comprises an energy density about 30 times larger: $\epsilon_{\text{MWB}}(z=0) \approx 4.2 \times 10^{-13} \text{ erg cm}^{-3}$) in any other waveband (see Fig. 1). For comparison, the global energy density of the X-ray background is $\epsilon_{\text{XRB}}(z=0) \approx 8 \times 10^{-17} \text{ erg cm}^{-3}$. This already indicates that nuclear activity, which yields a roughly flat spectral energy distribution over many orders of magnitude, is unlikely to contribute much (but see below).

Contribution of galaxies to the IR background: kinematic models

As mentioned above, the deep K-band counts (Gardner *et al.* 1993) may already have directly resolved most of the extragalactic near IR background. On the other hand, the deepest far-IR survey available so far (Hacking 1987; Hacking & Houck 1987) with a flux limit of 50 mJy at $60 \mu\text{m}$, extends only out to a median redshift $z \simeq 0.08$ (Ashby *et al.* 1994). Nevertheless, the IRAS $60 \mu\text{m}$ counts have provided some evidence of a substantial cosmological evolution of galaxies in the far-IR, consistent with that inferred from VLA surveys at sub-mJy levels (Windhorst *et al.* 1993 and references therein), given the tight correlation between radio and far-IR emissions of disk and irregular galaxies (Hacking *et al.* 1987; Danese *et al.* 1987; Lonsdale & Hacking 1989; Rowan-Robinson *et al.* 1993).

Simple estimates of the integrated far-IR emission of galaxies have been produced by several authors adopting empirical evolution models for the local luminosity function, consistent with the IRAS counts (Franceschini *et al.* 1991b; Hacking & Soifer 1991; Beichman & Helou 1991; Oliver *et al.* 1992). More physical models have been considered by Wang (1991a,b) who has taken into account the evolution of the dust mass in galaxies (assumed to be proportional to the mass of interstellar gas and to its metallicity) and of the dust emissivity (the total power emitted by each grain was taken to be proportional to the star formation rate). Treyer & Silk (1993) have exploited the kinematic evolution models by Cole *et al.* (1992), matching optical and near-IR counts of galaxies and redshift distributions. One model includes a new population of low luminosity blue galaxies showing up at $z \gtrsim 0.7$ and gradually vanishing at lower redshifts, because of rapid fading, merging or self-disruption. In a second model, the evolution of dwarf blue galaxies follows the evolution of the number density of dark matter halos in the cold dark matter scenario, computed using the Press & Schechter (1974) formalism. The models have been extended throughout the electromagnetic spectrum, from radio to X-rays, using observed correlations to relate the blue luminosity to emissions in other wavebands. The far-IR emission of local galaxies is assumed to be non-evolving, while that of dwarf blue galaxies is calculated as $L_{\text{fir}} = [\exp(\tau) - 1]L_{\text{B}}$; results are presented for a constant optical depth $\tau = 1$.

A thorough treatment should take into account: the evolution of stellar populations in galaxies of different morphological types; the evolution of dust properties, abundance and distribution and the corresponding evolution of extinction of starlight and re-emission in the far-IR; the observed properties (spectral energy distributions and luminosity functions) of galaxies of different morphological types in the local universe.

Important constraints are provided by the deep counts in the optical and near-IR bands, by the IRAS 60 μm counts and (thanks to the tight far-IR/radio correlation for galaxies) by the sub-mJy VLA counts (probably dominated by galaxies with active star formation, cf. Benn et al 1993), as well as by related statistics (luminosity, redshift and color distributions).

A simple self-consistent model

Mazzei *et al.* (1992, 1994) were the first to attempt an extension up to far-IR/sub-mm wavelengths of population synthesis models for the chemical and photometric evolution of galaxies. Two extreme cases were analyzed. On one side, disk galaxies, characterized by dissipational collapse, with slow gas depletion, i.e. the star formation rate (SFR) never much higher than today (Sandage 1986). At the other side, spheroidal galaxies thought to have used up most of their gas to form stars in a time short compared with the collapse time, i.e. with a spectacularly large initial SFR.

For each case, chemical and photometric evolution models were constructed in the usual

way, adopting a Schmidt law for the evolution of the star formation rate and the standard Salpeter or Scalo Initial Mass Functions (IMFs). Simple assumptions were adopted for the dust component, i.e.:

- i) the dust to gas ratio is proportional to some power of the metallicity, as proposed by Guiderdoni & Rocca-Volmerange (1987);
- ii) stars and dust are well mixed;
- iii) the “standard” grain model (Mathis *et al.* 1977; Draine & Lee 1984), including a power law grain size distribution, holds at any time.

The local optical depth is obtained from the condition that the amount of absorbed starlight equals the far-IR emission; its evolution follows directly from that of the gas fraction and of the metallicity, computed using the standard equations for chemical evolution for given SFR and IMF.

The models allow for two dust components: cold dust, heated by the general interstellar radiation field, and warm dust associated to starforming regions. They include PAH molecules (Puget & Léger 1989) and emission from circumstellar dust shells, primarily associated to stars in the final stage of evolution along the asymptotic giant branch.

The standard view that the metallicity and the star formation rate in galactic disks do not vary much after a few Gyr from the formation of the disk imply that both the bolometric luminosity of these galaxies and the re-emission of their interstellar dust vary only slowly throughout most of the galaxy lifetime (Fig. 2). Such weak evolution cannot account for the substantial cosmological evolution indicated by the deep IRAS counts and by the sub-mJy radio counts (linked to far-IR counts by the tight far-IR/radio correlation exhibited by galaxies).

On the contrary, dramatic far-IR evolution is expected for early-type galaxies due to the fast (exponential with a timescale of a few Gyr) decrease of the SFR with increasing galactic age. On one hand, the bolometric luminosity increases by a substantial factor with decreasing galactic age, T : models generally indicate a factor $\simeq 10$ increase of L_{bol} from $T = 15$ Gyr to $T = 2$ Gyr). On the other hand, the far-IR to optical luminosity ratio increases from local values $\lesssim 10^{-2}$ (Mazzei & De Zotti 1994a) to $\simeq 1$ or even $\gg 1$ at early times.

Under the assumptions listed above, the key parameter is the gas consumption rate: in the case of a fast conversion of gas into stars, the far-IR emission is never dominant; but if the gas depletion is slower the galaxy may experience a prolonged opaque phase, with most of the luminosity emitted in the far-IR (Fig. 3). Examples of evolution of the spectral energy distribution of spheroidal galaxies predicted by different models are shown in Fig. 4.

It has been stressed by many authors (e.g. van den Berg 1990, 1992; Wang 1991 a,b,c; Kormendy and Sanders 1992) that, due to the fast metal enrichment of primordial galaxies, substantial dust extinction and far-IR emission are expected during early phases of galaxy evolution.

As illustrated by Fig. 3, if the dust to gas ratio is roughly proportional to the metallicity, the effective dust opacity may have very different histories, depending on the behaviour of the SFR, of the IMF, but possibly also on external effects such as infall of intergalactic material or merging of gas rich companions. In particular, if the gas depletion is relatively slow, the galaxy may experience an extremely optically thick phase. An example of the latter situation may be the ultraluminous galaxy IRAS F10214+4724 (Rowan-Robinson *et al.* 1991; Lawrence *et al.* 1993; Mazzei & De Zotti 1994b; see Fig. 5).

Under some circumstances (see Fig. 3), the strongly optically thick phase may last several Gyr. It is presently unknown how frequently such situation may occur. However, some recent results provide indirect indications that strong extinction may indeed be common during early evolutionary phases (Franceschini *et al.* 1994).

The standard population synthesis models for galaxy evolution (Guiderdoni & Rocca-Volmerange 1990; Yoshii & Takahara 1988; Charlot & Bruzual 1991) predict that galaxies, and particularly early-type galaxies, should have been brighter in the past as a consequence of a more active star formation associated to a larger gas fraction. Thus, the excess surface density of galaxies, in comparison to expectations in the absence of evolution, was attributed to the brightening of high- z galaxies, which increases the sampled volume.

However, spectroscopic work has shown that the excess faint counts are rather due to dwarf galaxies at relatively low redshifts ($z \sim 0.3\text{--}0.7$) and that there is a remarkable lack of high redshift galaxies in optically selected samples down to $B = 24\text{--}25$ (Broadhurst *et al.* 1988; Colless *et al.* 1990, 1993; Cowie *et al.* 1991). In fact, none of the 100 (out of a total of 104) galaxies with measured redshifts in the complete sample with $B < 22.5$ of Colless *et al.* (1993) has $z > 0.7$; the highest redshift of the complete sample by Cowie *et al.* (1991) with $B < 24$ is $z = 0.73$. Colless *et al.* (1993) conclude that their data allow no more than 1 mag of luminosity evolution of L_* galaxies by $z = 1$.

An attractive explanation of these results is that present day luminous galaxies formed late as the result of merging, perhaps of the same faint blue galaxies which appear to be much more numerous at intermediate redshifts than they are locally. This hypothesis, however, faces some serious problems:

- i) the thinness of disks implies that only a few percent of the baryonic mass can have been accreted in the last several Gyr (Ostriker 1990; Toth & Ostriker 1992; Quinn *et al.* 1993);
- ii) colors and the existence of a well defined “fundamental plane” for early type galaxies

provide strong indications that they are old ($z_F > 2$) and essentially coeval, later additions probably corresponding to no more than 10% of the present luminosity (Renzini 1993);

ii) faint galaxies in the relevant magnitude range ($22 < B < 26$) appear to be less spatially clustered than local galaxies, contrary to expectations if they are in the process of merging (Efstathiou *et al.* 1991; Pritchett & Infante 1992; Roche *et al.* 1993);

iii) the merging timescale needed to explain the faint galaxy counts appears to be uncomfortably higher than current estimates based on local galaxy samples (Carlberg 1992);

iv) the total luminosity in local ellipticals is lower than expected if they are the merger products of the “excess” faint blue galaxies with $B < 24$ (Dalcanton 1993).

On the other hand, evidences of substantial amounts of dust at high z (up to $z = 4.69$) were provided by detection of QSOs at mm wavelengths (Andreani *et al.* 1993; McMahon *et al.* 1994; Isaak *et al.* 1994). Also, enormous dust masses are indicated by sub-mm detections (Hughes *et al.* 1994) of the high z radio galaxies 4C41.17 ($z = 3.8$) and 53W002 ($z = 2.39$).

A consistent picture obtains assuming that, during the phases of intense star formation, most of the optical radiation was absorbed by dust and reradiated in the far-IR (Franceschini *et al.* 1994). In this case, less than 1% of galaxies in the range $21 < B < 22.5$ and less than 10% of those with $B < 24$ are expected at $z > 0.7$ (in the absence of dust extinction, the standard evolutionary models predict that 40% of galaxies with $21 < B < 22.5$ and $\sim 50\%$ of those with $B < 24$ should have $z > 0.7$). Moreover, the model can account for the deep $60\mu\text{m}$ IRAS counts and, exploiting the far-IR/radio correlation for galaxies, can explain most of the observed sub-mJy flattening of radio counts over a couple of decades in flux. Also, dust extinction may explain the failure to detect Ly α emission in searches for primeval galaxies (De Propris *et al.* 1993; Djorgovski & Thompson 1992).

This scenario entails a number of testable predictions:

i) the redshift distribution of galaxies in the deep ($S_{60\mu\text{m}} > 50\text{ mJy}$) IRAS sample (Hacking & Houck 1987; Hacking *et al.* 1987; Ashby *et al.* 1994) should have a tail at significant z : we expect $\sim 30\text{--}40$ galaxies at $z > 0.1$ and about 5-10 at $z > 0.3$; in the absence of evolution, only about 18 should be at $z > 0.1$ and essentially none at $z > 0.3$;

ii) a high redshift peak should quickly develop in the redshift distribution at fainter flux limits, easily reachable with ISO;

iii) a substantial fraction of high- z galaxies should also be present among sub-mJy radio sources;

iv) large ellipticals should virtually disappear at $B \simeq 22\text{--}24$, an effect that could be tested by morphological studies with HST.

Estimates of possible contributions of galaxies to the background, under different assumptions

(no evolution, moderately opaque case, opaque case), are shown in Fig. 6. The expected contribution to the near-IR background is relatively insensitive to the effect of dust extinction. The measurements of the expected backgrounds are well within the DIRBE sensitivity limits. The great difficulty, however, is the subtraction of foreground emissions.

Pre-galactic star formation

The possibility that early structures, at $z \sim 5-100$, could have led to copious star formation, producing both an intense background and dust capable of reprocessing it, has been extensively discussed by Bond *et al.* (1991). In this case, essentially all the energy produced by nuclear reactions comes out at far-IR/sub-mm wavelengths. The peak wavelength depends on the redshift and temperature distributions of the dust but, for a relatively broad range of parameter values, occurs at $\lambda \sim 600 \mu\text{m}$. As shown by Wright *et al.* (1994), only one of the many models worked out by Bond *et al.* (1991) is compatible with the COBE/FIRAS data.

Constraints on dust enshrouded AGN populations

As already mentioned, canonical AGNs probably make a minor contribution to the IR background. In fact, quasars were very rarely detected in the IRAS survey. The list of previously unknown quasars discovered by IRAS, compiled by Clowes *et al.* (1991), contains only eleven objects, a number comparable to that of previously cataloged quasars included in the IRAS Point Source Catalog (cf. Soifer *et al.* 1987). The question then arose whether they constitute a new population of infrared loud quasars, perhaps corresponding to an early phase of the evolution, when the active nucleus was enshrouded by a dense cloud of dust and gas which is gradually consumed and/or swept away as the luminosity of the nucleus increases (Sanders *et al.* 1988; Low *et al.* 1988). The work of Low *et al.* (1989), Sanders *et al.* (1989) and Clowes *et al.* (1991), however, suggests that IRAS selected quasars are not very special compared with other quasars; they simply correspond to the reddest tail of the general population, as expected as a consequence of the far-IR selection, and are mainly demonstrating the incompleteness of the optical bright quasar surveys.

On the other hand, AGNs have been so far identified through their optical properties. It is still possible that there exists a significant population of heavily obscured AGNs which are optically very faint, but bright in the far-IR. It has been argued that dust enshrouded AGNs can contribute significantly to power the highest luminosity IRAS galaxies (e.g. Sanders *et al.* 1987). Two very well studied examples of very high infrared luminosity galaxies are Arp 220 (IC 4553; Soifer *et al.* 1984) and NCG 6240 (Wright *et al.* 1984); both show strong evidence for an active nucleus. The extreme far-IR galaxies IRAS F10214+4724 (Rowan-Robinson *et*

al. 1991; Lawrence *et al.* 1993; Elston *et al.* 1994), IRAS F15307+3252 (Cutri *et al* 1994), and IRAS 09104+4109 (Kleinman & Keel 1987; Kleinmann *et al* 1988; Hines & Wills 1993) all clearly harbor an AGN (although its relative contribution to the bolometric luminosity is still unclear).

In a different context, extreme absorption has been postulated by Setti & Woltjer (1989), Morisawa *et al.* (1990), and Grindlay & Luke (1990) to account for the spectrum of the X-ray background above $\simeq 3$ keV, in the framework of unified models for AGNs. According to these models, the central powerhouse is surrounded, at a distance of several parsecs, by obscuring matter, probably having toroidal geometry. Depending on whether our view is down the axis or is occulted by the torus, we see a broad line AGN (type 1 Seyfert or QSO) or a narrow line one (type 2 Seyfert or hypothetical type 2 QSO), respectively. For reasonable values of tori masses and sizes, absorbing columns up to 10^{24} – 10^{25} cm $^{-2}$ can be expected, implying that the nuclear X-ray emission can be absorbed up to ~ 20 – 30 keV, depending on the torus column density and geometry. The density of strongly absorbed sources required to account for the X-ray background above 3 keV is a few times larger than that of type 1 AGNs and their cosmological evolution must be similarly strong (Comastri *et al.* 1994; Madau *et al.* 1993, 1994).

If such highly obscured AGNs emit most of their power in the far-IR, their contribution to the far-IR background may be substantial, as illustrated by the following simple calculation. The local energy density produced by UV-excess AGNs can be estimated from B counts as:

$$\epsilon_{\text{AGN}} \simeq \frac{4\pi}{c} \kappa \cdot I_B \simeq \frac{4\pi}{c} \kappa \nu_B \int_{S_{\min}}^{S_{\max}} S \cdot N_B(S) dS .$$

Assuming a ratio of bolometric to B-band flux $\kappa = 30$ (Padovani 1989) and an effective redshift $z_{\text{AGN}} = 1.5$ we find $\epsilon_{\text{AGN}}(z = 0) \approx 1.5 \times 10^{-15}$ erg cm $^{-3}$, not far from the estimated contribution of galaxies to the background at $\lambda > 10 \mu\text{m}$ ($\epsilon_{\text{gal,FIR}}(z = 0) \approx 4 \times 10^{-15}$ erg cm $^{-3}$).

Since the estimated contribution from galaxies is already close to the COBE/FIRAS limits at sub-mm wavelengths, these limits set significant constraints on a population of dust-enshrouded AGNs, with a bolometric emission comparable to that of canonical AGNs. If they are to account for the hard X-ray background, they would yield a contribution to the far-IR background potentially detectable by COBE/DIRBE.

Note that the quoted radiation energy density due to optically selected AGNs corresponds to a quite low mass density of collapsed nuclei: $(H_0/50)^2 \Omega_{\text{AGN}} \simeq 5.5 \times 10^{-6} (\kappa/30) (\eta/0.1)^{-1}$, Ω being the mass density in units of the critical density and η the mass to energy conversion efficiency (Padovani *et al.* 1990). It follows that the available data on diffuse backgrounds (cf. e.g. Fig. 1) constrain the mass density that can be contributed by black holes built up by accretion with high radiation efficiency. In particular, the limits on the extragalactic far-IR background (taking the Oliver *et al.* (1992) 100 μm upper limit as a reference value) imply that the mass

density of dust enshrouded AGNs has to be $(H_0/50)^2 \Omega_{\text{AGN}} \lesssim 3.3 \times 10^{-5} (\eta/0.1)^{-1} (\kappa/30)$.

Conclusions

There are indications that a large fraction of starlight is absorbed by dust and re-radiated at far-IR wavelengths. If so, surveys at longer wavelengths, where the effect of dust extinction is smaller, should contain higher fractions of high- z galaxies. A hint in this direction might be seen in the I-band sample of Lilly (1993), where 6 out of 25 confirmed galaxies are at $z > 0.8$.

At mid-IR wavelengths three effects concur in easing the detection of high- z galaxies: the decreasing effect of dust extinction; the positive K-correction (the stellar SED peaks at $\lambda \simeq 1 \mu\text{m}$); the positive luminosity evolution. The deep survey with the most sensitive filter of ISOCAM (LW2, $5 < \lambda < 8.5 \mu\text{m}$) should detect $\sim 2\text{--}3$ galaxies per arcmin 2 , i.e. 10–20 galaxies per frame; a good fraction of these should be at $z \gtrsim 1$.

Our models imply that early type galaxies with intense star formation could start to show up in $60 \mu\text{m}$ surveys at $S_{60\mu\text{m}} \lesssim 100 \text{ mJy}$. A few galaxies in the deep ($S_{60\mu\text{m}} > 50 \text{ mJy}$) sample by Hacking *et al.* (1987) are expected to be early type galaxies at $z > 0.6$.

ISO should be able to cover a few deg 2 to $S_{60\mu\text{m}} \sim 10 \text{ mJy}$; various tens of dusty galaxies may be detected; we expect that a good fraction of them are at significant redshifts.

Some of the galaxies detected in the deepest (sub-mJy) radio surveys may also be at significant z . They are expected to be very faint in the optical (up to $B \simeq 28$).

Optically selected AGNs are minor contributors to the far-IR background. A substantial contribution, however, may be expected from a yet undetected population of highly obscured nuclei, such as that advocated to explain the X-ray background above 3 keV.

Tight constraints on the evolution of dusty galaxies and on the density and evolution of dust enshrouded AGN are expected from COBE/DIRBE data, when the delicate subtraction of foreground emission will be completed. As shown by Wright *et al.* (1994), COBE/FIRAS limits on the sub-mm background have already ruled out a large variety of models postulating intense pre-galactic star formation (Bond *et al.* 1991) as well as of non-standard models, such as those invoking early bursts of Population III stars producing a large fraction of the cosmic helium abundance (Negroponte *et al.* 1981; Wright 1981).

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References

Andreani, P., F. La Franca, and S. Cristiani, *M. N. R. A. S.*, **261**, L35–L38 1993.

Ashby, M.L.N., P.B. Hacking, J.R. Houck, B.T. Soifer, and E.W. Weisstein, *Ap. J.*, submitted, 1994.

Beichman, C.A. and G., Helou, *Ap. J.*, **370**, L1–L4 1991.

Benn, C.R., M. Rowan-Robinson, R.G. McMahon, T.J. Broadhurst, and A. Lawrence, *M. N. R. A. S.*, **263**, 98–112 1993.

Bond, J.R., B.J. Carr, and C.J. Hogan, *Ap. J.*, **367**, 420–454 1991.

Broadhurst, T.J., R. Ellis, and T. Shanks, *M. N. R. A. S.*, **235**, 827–840 1988.

Carlberg, R.G., *Ap. J.*, **399**, L31–L35 1992.

Charlot, S., and G. Bruzual, *Ap. J.*, **367**, 126–141 1991.

Clowes, R.G., S.K. Leggett, and A. Savage, *M. N. R. A. S.*, **250**, 597–601 1991.

Cole, S., M.A. Treyer, and J. Silk, *Ap. J.*, **385**, 9–25 1992.

Colless, M., R. Ellis, K. Taylor, and R. Hook, *M. N. R. A. S.*, **244**, 408–420 1990.

Colless, M., R.S. Ellis, K. Taylor, and B. Peterson *M. N. R. A. S.*, **261**, 19–38 1993.

Comastri, A., G. Setti, G. Zamorani, and G. Hasinger, *Astr. Ap.*, in press, 1994.

Cowie, L.L., A. Songaila, and E.M. Hu, *Nature*, **354**, 460–462 1991.

Cutri, R.M., J.P. Huchra, F.J. Low, R.L. Brown, and P.A. Vanden Bout, *Ap. J.*, **424**, L65–L68 1994.

Dalcanton, J.J., *Ap. J.*, **415**, L87–L90 1993.

Danese, L., G. De Zotti, A. Franceschini, and L. Toffolatti, *Ap. J.*, **318**, L15–L19 1987.

De Jager, O.C., F.W. Stecker, and M.H. Salamon, *Nature*, **369**, 294–296 1994.

De Propris, R., C.J. Pritchett, D.A. Hartwick, and P. Hickson, *A. J.*, **105**, 1243–1250 1993.

Djorgovski, G., and D.J. Thompson, in *The Stellar Populations of Galaxies*, IAU Symp. 149, B. Barbuy and A. Renzini Eds. (Kluwer, Dordrecht), 1992.

Draine, B.T., and H.M. Lee, *Ap. J.*, **285**, 89–102 1984.

Dwek, E., and J. Slavin, *Ap. J.*, in press, 1994.

Efstathiou, G., G. Bernstein, N. Katz, A.J. Tyson, and P. Guhathakurta, *Ap. J.*, **380**, L47–L50 1991.

Elston, R., P.J. McCarthy, P. Eisenhardt, M. Dickinson, H. Spinrad, B.T. Januzzi, and P. Maloney, *A. J.*, **107**, 910–919 1994.

Franceschini, A., P. Mazzei and G. De Zotti, Proceedings of the XIth Moriond Astrophysical Meeting “*The early observable universe from diffuse backgrounds*”, B. Rocca-Volmerange, J.M. Deharveng & J. Trân Thanh Vân eds., Editions Frontières, p. 249–255, 1991a.

Franceschini, A., P. Mazzei, G. De Zotti, and L. Danese, *Ap. J.*, **427**, 140–154 1994.

Franceschini, A., L. Toffolatti, P. Mazzei, L. Danese, and G. De Zotti, *Astr. Ap. Suppl.*, **89**, 285–310 1991b.

Gardner, J.P., L.L. Cowie, and R.J. Wainscoat, *Ap. J.*, **415**, L9–L12 1993.

Grindlay, J.E., and M. Luke, in *High Resolution X-ray Spectroscopy of Cosmic Plasmas*, proc. IAU Coll. 115, eds P. Gorenstein and M.V. Zombeck, Kluwer, Dordrecht, p. 276–280, 1990.

Guiderdoni, B., and B. Rocca–Volmerange, *Astr. Ap.*, **186**, 1–18 1987.

Guiderdoni, B., and B. Rocca–Volmerange, *Astr. Ap.*, **227**, 362–374 1990.

Hacking, P., Ph.D. thesis, Cornell University, 1987.

Hacking, P.B., J.J. Condon, and J.R. Houck, *Ap. J.*, **316**, L15–L18 1987.

Hacking, P. and J.R. Houck, *Ap. J. Suppl.*, **63**, 311–330 1987.

Hacking, P.B., and B.T. Soifer, *Ap. J.*, **367**, L49–L52 1991.

Hauser, M.G., T. Kelsall, S.H. Jr. Moseley, R.F. Silverberg, T. Murdock, G. Toller, W. Spiesman, and J. Weiland, in *Proc. AIP Conference “After the First Three Minutes”* eds. Holt, S.S., Bennett, C.L., Trimble, V., **222**, p.161–170 1991.

Hines, D.C., and B.J. Wills, *Ap. J.*, **415**, 82–92 1993.

Hughes, D., J. Dunlop, S. Rawlings, and S. Eales, paper presented at the European and National Astronomy Meeting, Edinburgh, 1994.

Isaak, K.G., R.G. McMahon, R.E. Ellis, and S. Withington, *M. N. R. A. S.*, **269**, L28–L32 1994.

Lilly, S.J. *Ap. J.*, **411**, 501–512 1993.

Kleinmann, S.G., D. Hamilton, W.C. Keel, C.G. Wynn-Williams, S.A. Eales, E.E. Becklin, and K.D. Kuntz, *Ap. J.*, **328**, 161–169 1988.

Kleinmann, S.G., and W.C. Keel, in *Star Formation in Galaxies*, ed. C.J. Lonsdale, NASA Conf. Publ. 2466, 559–562, 1987.

Kormendy, J., and D.B. Sanders, *Ap. J.*, **390**, L53–L56 1992.

Lange, A.E., P.L. Richards, S. Hayakawa, T. Matsumoto, H. Matsuo, H. Murakami, and S. Sato, 1990, private comm. to Hauser *et al.* 1991.

Lawrence, A., *et al.*, *M. N. R. A. S.*, **260**, 28–44 1993.

Lonsdale, C., and P. Hacking, *Ap. J.*, **339**, 712–722 1989.

Low, F.J., R.M. Cutri, S.G. Kleinmann, and J.P. Huchra, *Ap. J.*, **340**, L1–L4 1989.

Low, F.J., J.P. Huchra, S.G. Kleinmann, and R.M. Cutri, *Ap. J.*, **327**, L41–L44 1988.

Madau, P., G. Ghisellini, and A.C. Fabian, *Ap. J.*, **410**, L7–L10 1993.

Madau, P., G. Ghisellini, and A.C. Fabian, *M. N. R. A. S.*, in press, 1994.

Mather, J.C., *et al.*, *Ap. J.*, **420**, 439–444 1994.

Mathis, J.S., W. Rumpl, and K.H. Nordsieck, *Ap. J.*, **217**, 425–433 1977.

Matsumoto, T., S. Hayakawa, H. Matsuo, H. Murakami, S. Sato, A.E. Lange, and P.L. Richards, *Ap. J.*, **329**, 567–580 1988.

Mazzei, P., and G. De Zotti, *Ap. J.*, **426**, 97–104 1994a.

Mazzei, P., and G. De Zotti, *M. N. R. A. S.*, **266**, L5–L9 1994b.

Mazzei, P., C. Xu, and G. De Zotti, *Astr. Ap.*, **256**, 45–55 1992.

Mazzei, P., G. De Zotti, and C. Xu, *Ap. J.*, **422**, 81–91 1994.

McMahon, R.G., A. Omont, J. Bergeron, E. Kreysa, and C.G.T. Haslam, *M. N. R. A. S.*, **267**, L9–L12 1994.

Morisawa, K., M. Matsuoka, F. Takahara, and L. Piro, *Astr. Ap.*, **236**, 299–311 1990.

Negroponte, J., M. Rowan-Robinson, and J. Silk, *Ap. J.*, **248**, 38–50 1981.

Noda, M., V.V. Christov, H. Matsuura, T. Matsumoto, S. Matsura, K. Noguchi, S. Sato, and H. Murakami, *Ap. J.*, **391**, 456–465 1992.

Oliver, S.J., M. Rowan-Robinson, and W. Saunders, *M. N. R. A. S.*, **256**, 15–18P 1992.

Ostriker, J.P., in *Evolution of the Universe of Galaxies*, ed R.G. Kron, p. 10–18, 1990.

Padovani, P., *Astr. Ap.*, **209**, 27–40 1989.

Padovani, P., R. Burg, and R.A. Edelson *Ap. J.*, **353**, 438–448 1990.

Press, W.H., and P. Schechter, *Ap. J.*, **187**, 425–438 1974.

Pritchett, C.J., and L. Infante, *Ap. J.*, **399**, L35–L38 1992.

Puget, J.L., and A. Léger, *Ann. Rev. Astr. Astrophys.*, **27**, 161–195 1989.

Quinn, P.J., L. Hernquist, and D.P. Fullagar, *Ap. J.*, **74–93**, 1993.

Renzini, A., *Texas/Pascos '92: Relativistic Astrophysics and Particle Cosmology*, C.W. Akerlof and M.A. Srednicki eds., *Ann. N. Y. Acad. Sci.*, **688**, 124–135, 1993.

Roche, N., T. Shanks, N. Metcalfe, and R. Fong, *M. N. R. A. S.*, **263**, 360–368 1993.

Rowan-Robinson M. *et al.*, *Nature*, **351**, 719–722 1991.

Rowan-Robinson, M., C.R. Benn, A. Lawrence, R.G. McMahon, and T.J. Broadhurst, *M. N. R. A. S.*, **263**, 123–130 1993.

Sandage, A., *Astr. Ap.*, **161**, 89–97 1986.

Sanders, D.B., *et al.*, in *Star Formation in Galaxies*, ed. C.J. Lonsdale, NASA Conf. Publ. 2466, 411–420, 1987.

Sanders, D.B., B.T. Soifer, J.H. Elias, G. Neugebauer, and K. Matthews, *Ap. J.*, **328**, L35–L38 1988.

Sanders, D.B., E.S. Phinney, G. Neugebauer, B.T. Soifer, and K. Matthews, *Ap. J.*, **347**, 29–44 1989.

Setti, G., and L. Woltjer, *Astr. Ap.*, **224**, L21–L23 1989.

Soifer, B.T., *et al.*, *Ap. J.*, **283**, L1–L4 1984.

Soifer, B.T., Houck, J.R. & Neugebauer, G., *Ann. Rev. Astr. Astrophys.*, **25**, 187–230 1987.

Stecker, F.W. and O.C. De Jager, *Ap. J.*, **415**, L71–L74 1993.

Stecker, F.W., O.C. De Jager, and M.H. Salamon, *Ap. J.*, **390**, L49–L52 1992.

Toth, G. and J.P. Ostriker, *Ap. J.*, **389**, 5–26 1992.

Treyer, M.A., and J. Silk, *Ap. J.*, **408**, L1–L4 1993.

van den Berg, S., *Publs astr. Soc. Pacif.*, **102**, 503–510 1990.

van den Berg, S., *M. N. R. A. S.*, **255**, 29–32P 1992.

Wang, B., *Ap. J.*, **374**, 456–464 1991a.

Wang, B., *Ap. J.*, **374**, 465–474 1991b.

Wang, B., *Ap. J.*, **383**, L37–L40 1991c.

Windhorst, R.A., E.B. Fomalont, R.B. Partridge, and J.D. Lowenthal, *Ap. J.*, **405**, 498–517 1993.

Wright, E.L., *Ap. J.*, **250**, 1–14 1981.

Wright, E.L., *et al.*, *Ap. J.*, **420**, 450–456 1994.

Wright, G.S., R.D. Joseph, and W.P.S. Meikle, *Nature*, **309**, 430–431 1984.

Yoshii, Y. and F. Takahara, *Ap. J.*, **326**, 1–14 1988.

Figure Captions

Figure 1. Measurements of and constraints on the brightness per logarithmic frequency interval of the extragalactic background from radio to γ -ray frequencies.

Figure 2. Evolution with galactic age of the spectrum of a disk galaxy (Mazzei *et al.* 1992).

Figure 3. Evolution of the effective optical depth, τ , of the gas metallicity, Z (in solar units), and of the gas fraction, f , for an early type galaxy for different choices of the SFR and of the lower mass limit, m_l (in solar masses); see Mazzei *et al.* (1994) for more details. A Schmidt parametrization has been adopted for the SFR ($\psi(t) = \psi_0 f^n M_{\odot} \text{yr}^{-1}$). A Salpeter form has been adopted for the IMF. If a constant fraction of metals is locked up in dust grains, τ is proportional to fZ .

Figure 4. Evolution with galactic age of the spectrum of an early type galaxy (Mazzei *et al.* 1994), in the case of a moderate (upper panel) or strong dust extinction during early phases. The spectrum at $T = 15$ Gyr is compared with data for nearby ellipticals (see Mazzei *et al.* 1994).

Figure 5. Spectral energy distribution of an early type galaxy with strong extinction during early evolutionary phases (cf. Fig. 4), for two values of the galactic age T , compared with observational data for the galaxy IRAS F10214 + 4724 (see Mazzei and De Zotti 1994b).

Figure 6. Extragalactic background light at IR to sub-mm wavelengths. Data and upper limits are from Hauser *et al.* (1991), Noda *et al.* (1992) as revised by Franceschini *et al.* (1991a), Oliver *et al.* (1992) and Dwek & Slavin (1994) (short-dashed line). Curve *a* corresponds to no evolution, curves *b* and *c* to moderate or strong extinction, respectively, of early type galaxies during early evolutionary phases; curve *d* is the integrated starlight of distant galaxies in the near-IR, derived from models fitting the deep K-band counts. Curve *S* shows the contribution of stars in our own Galaxy, at high galactic latitudes (see Franceschini *et al.* 1991b). The DIRBE sensitivity as function of λ is also shown.